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# A New Analysis of Charge Symmetry Violation in Parton Distributions

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## Abstract

To date, the strongest indication of charge symmetry violation in parton distributions has been obtained by comparing the  $F_2$  structure functions from CCFR neutrino data and NMC muon data. We show that in order to make precise tests of charge symmetry with the neutrino data, two conditions must be satisfied. First, the nuclear shadowing calculations must be made explicitly for neutrinos, not simply taken from muon data on nuclei. Second, the contribution of strange and charm quarks should be calculated explicitly using next-to-leading order [NLO] QCD, and the “slow rescaling” charm threshold correction should not be applied to the neutrino data. When these criteria are satisfied, the comparison is consistent with charge symmetry within the experimental errors and the present uncertainty in the strange quark distribution of the nucleon.

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In recent years there have been a number of surprising discoveries concerning the parton distributions of the nucleon. In the valence distributions it now seems likely that the  $d/u$  ratio at large- $x$  is consistent with the expectations of perturbative QCD [1], when for many years it seemed that the ratio might vanish in that region. However, it is in the sea that one has found the biggest surprises. Following the discovery of a violation of the Gottfried sum-rule by the New Muon Collaboration [NMC] [2], the E866 experiment at Fermilab has mapped out a clear violation of the perturbative QCD expectation of equal numbers of  $\bar{d}d$  and  $\bar{u}u$  pairs in the sea of the proton [3]. Most recently, a careful comparison of the  $F_2$  structure functions measured in  $\nu$  reactions by the CCFR Collaboration [4] and  $\mu$  deep inelastic scattering by the NMC group [5], has revealed [6] a discrepancy that suggests a violation of charge symmetry in the parton distributions of the nucleon, at a level significantly larger than the expectations of either theory [7] or other experiments [8].

Charge symmetry, which is related to the invariance of the strong Hamiltonian under rotations of 180 degrees about the 2-axis in isospace [9], implies the equality of the  $d$ -distribution in the proton,  $d^p$ , and the  $u$ -distribution in the neutron,  $u^n$ , etc. Charge symmetry implies analogous relations for the antiquark distributions. It is implicit in the standard notation for parton distributions, with  $d \equiv d^p = u^n, u \equiv u^p = d^n$ , and so on. In view of the importance of any significant violation of charge symmetry it is vital to reexamine every aspect of the analysis of the CCFR and NMC data and, in particular, the difference

$$\frac{5}{6}F_2^{\nu N}(x, Q^2) - 3F_2^{\mu N}(x, Q^2) \quad , \quad (1)$$

on an isoscalar target – after corrections for  $s$  and  $c$  quarks, this difference should be strictly zero for all  $x$  if charge symmetry is exact.

The comparison between the  $\nu$  and  $\mu$  data is complicated by the fact that the  $\nu$  data are taken on an Fe target. The heavy target is necessary because of the low event rates for neutrino experiments. Before these data can be compared with the muon data taken on deuterium, a number of corrections must be made. In what follows we re-examine all

of these corrections. We can now make rather accurate estimates of these corrections as a result of the rapid experimental [10] and theoretical developments [11, 12, 13, 14, 15] in our understanding of charm structure functions. In particular, we have applied a next-to-leading order [NLO] calculation of the charm quark contribution [15] to both the  $\nu$  and  $\mu$  experiments, rather than applying a “slow rescaling” correction to the data, as has been the custom [4, 16]. In this way we can compare our theoretical NLO calculation directly with the data.

We shall see that, when *both* the  $\nu$  shadowing corrections [17] and the explicit charm production calculations are made with the best available theory, the residual discrepancy between the  $\nu$  and  $\mu$  data is much smaller than was suggested by earlier analysis. Our key results are summarized in Fig. 1, where the NLO results (triangles) should be compared with the data (filled circles). The difference  $(5/6)F_2^{\nu N} - 3F_2^{\mu N} \simeq (s + \bar{s})/2$  is quite sensitive to the strange distribution in the proton. Consequently, the agreement between experiment and theory will depend upon the particular parton distribution which is used. The data is still systematically above theoretical expectations based on the GRV98 [18] parametrization and on charge symmetry in the region  $0.008 \leq x \leq 0.08$  (these are the solid gray triangles in Fig. 1). However, the discrepancy is no longer outrageously large, as was suggested by earlier analysis. If one uses the MRST99 [19] or CTEQ5 [20] parton distributions for the NLO calculation of the structure functions (these are respectively the solid inverted triangles and the open triangles in Fig. 1), then the theory and experiment are in very good agreement. Both the MRST and CTEQ theoretical predictions are within one standard deviation of the experimental points for all  $x$ .

Our purpose here is to explain the meaning of the various theoretical and experimental points in Fig. 1, leading to our final conclusion concerning the level of charge symmetry violation consistent with the data. We begin with the corrections which are well under control.

Since Fe is not an isoscalar target, the structure function extracted from  $\nu$ -Fe scattering has to be converted to that of an isoscalar target. This is done by correcting for the

excess neutrons. This correction is relatively small and straightforward. The quantity  $5/6F_2^{\nu N} - 3F_2^{\mu N}$  contains contributions from both strange quarks and charge symmetry violation [CSV]. CSV tests which involve comparisons of  $F_2$  structure functions from muon and neutrino scattering are quite sensitive to the constraints on the strange quark distributions. The strange quark distribution has been measured independently in dimuon production in neutrino DIS by the CCFR Collaboration [21]. It is about a factor of two smaller than what is needed to resolve the original CCFR-NMC discrepancy. The difference,  $5/6F_2^{\nu N} - 3F_2^{\mu N}$ , is also sensitive to the difference between the strange and anti-strange quark distributions,  $xs(x) - x\bar{s}(x)$ . However, our previous analysis [6] has shown that a *negative* anti-strange quark distribution would be necessary to account for the whole NMC-CCFR discrepancy. We will come back to the uncertainties related to the strange quark distribution after having discussed the nuclear corrections.

### Shadowing for neutrinos

The difference between the NMC and CCFR structure functions is very sensitive to the nuclear corrections as can be seen in Fig. 1. Nuclear corrections for neutrinos (nuclear EMC effect, shadowing and anti-shadowing) are generally applied using phenomenological correction factors derived from charged lepton reactions. However, there is no reason that nuclear corrections for neutrinos and charged leptons should be identical. Since the original discrepancy between NMC and CCFR is significant in the small  $x$  region where nuclear shadowing is the dominant nuclear effect, we re-examined shadowing corrections in neutrino DIS. A detailed discussion can be found in Ref. [17]. Here, we summarize the main results.

We used a two phase model which has been successfully applied to the description of shadowing in charged lepton DIS [22, 23]. In generalizing this approach to weak currents, subtle differences between shadowing in neutrino and charged lepton DIS arise because of the partial conservation of axial currents (PCAC) and the coupling of the weak current to both vector and axial vector mesons. For the axial current, PCAC requires that shadowing in neutrino scattering for low  $Q^2 (\approx m_\pi^2)$  is determined by the absorption of pions on the

target [24], while at larger  $Q^2$ -values axial vector mesons (e.g. the  $a_1^+$  for the  $W^+$  charged current) become important. For the weak vector current one must include the  $\rho^+$  vector meson. Since the coupling constants are related by  $f_{\rho^+}^2 = f_{a_1}^2 = 2f_{\rho^0}^2$ , the  $a_1$  component is suppressed because of the larger  $a_1$  mass, and since the neutrino structure function is about a factor of four larger than the muon one at small  $x$ , the *relative* shadowing arising from VMD in neutrino DIS is roughly a factor of two smaller than in charged lepton DIS. For large  $Q^2$ -values, shadowing due to Pomeron exchange (which is of leading twist) becomes dominant, leading to identical (relative) shadowing in neutrino and charged lepton DIS.

In Fig. 1 the solid squares show the difference between the neutrino and muon structure functions, corrected for shadowing using the explicit calculation for neutrinos. This is to be compared with the corresponding difference when a  $Q^2$ -independent correction obtained from charged lepton DIS is used (open circles). There are differences between the two results in the small  $x$ -region, where  $Q^2$  is relatively small and the vector meson component plays a significant role. Here, the  $Q^2$  dependence of shadowing is also important. (Remember that the  $x$ -dependence of the shadowing corrections in charged lepton DIS, measured in fixed target experiments, is strongly correlated with their  $Q^2$ -dependence. In order to avoid very large shadowing corrections, we have made a cut on the data shown in Fig. 1 to remove all experimental points with  $Q^2 < 3 \text{ GeV}^2$ .)

We see that shadowing corrections made explicitly for neutrinos remove part of the original discrepancy between the NMC and CCFR data. In a LO analysis, the corrected data points (solid squares) should be compared to the LO result shown as open boxes. Such a comparison rests on the assumption that charm mass and charm threshold corrections have been taken into account properly by the slow rescaling corrections which have been applied to the data [4, 16]. This was the procedure adopted in our previous analysis [6]. As we have already noted, this approximation is no longer necessary, so in this paper, we perform a next-to-leading order analysis, which is summarized in the following section.

### Structure Function Calculations

There are two options for calculating the contribution of the charm quark to the

$F_2$  structure function for neutrino and muon deep inelastic scattering. One is to use the ACOT scheme [12], which changes the number of active flavors of the theory by introducing a charm distribution function. The other is to keep the number of active flavors fixed<sup>¶</sup>, in which case the charm quark contribution to  $F_2$  is calculated from the interaction between the probe and the gluons and light quarks in the target. In the neutral current case, the lowest order contribution is given by the boson - gluon fusion, which is an  $\mathcal{O}(\alpha_s)$  process. In the charged current case, the process  $W^+s \rightarrow c$ , which is of order  $\mathcal{O}(\alpha_s^0)$ , is the dominant contribution.

By definition, both schemes are equivalent in the region where  $Q^2$  is not much bigger than the square of the charm quark mass,  $m_c^2$ . When  $Q^2 \gg m_c^2$ , the ACOT scheme is superior to the FFNS because of the large logarithms in  $Q^2/m_c^2$  which appear in the partonic boson-gluon cross section. The ACOT scheme overcomes this problem by resumming the large logarithms in  $m_c^2$  through the introduction of a charm distribution. In practice, however, the implementation of the ACOT scheme in  $\nu$  DIS is only an additional complication. First, because the  $Q^2$  of the CCFR data in the small  $x$  region is not much larger than  $m_c^2$ . Second, the introduction of a charm distribution, and of subtraction terms to the boson-gluon cross section, will require the introduction of the  $W^-c \rightarrow s$  terms. This makes the case for charm tagging in the scattering process difficult, as the remaining  $\bar{c}$  anti quark (of the  $\bar{c}c$  pair) will have to hide in the hadronic debris of the reaction. Hence, we will adopt the FFNS for calculating the structure functions.

In the following, all the expressions for  $F_2$  are written as an average between proton and neutron targets for the muon case,

$$F_2^{\mu N}(x, Q^2) = \frac{1}{2}(F_2^{\mu p}(x, Q^2) + F_2^{\mu n}(x, Q^2)), \quad (2)$$

and an average between proton and neutron targets and neutrino and anti neutrino beams in the neutrino case:

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<sup>¶</sup>This scheme is generally referred to as the Fixed Flavor Number Scheme - FFNS.

$$F_2^{\nu N}(x, Q^2) = \frac{1}{4}(F_2^{\nu p}(x, Q^2) + F_2^{\nu n}(x, Q^2) + F_2^{\bar{\nu} p}(x, Q^2) + F_2^{\bar{\nu} n}(x, Q^2)). \quad (3)$$

For 3 active flavors, and using charge symmetry at the quark level, we have in the FFNS:

$$\begin{aligned} F_2^{\mu N}(x, Q^2) &= \frac{5}{18}x[(u + \bar{u} + d + \bar{d})(x, Q^2) + \frac{2}{5}(s + \bar{s})(x, Q^2)] \otimes C_q(x, Q^2) \\ &+ \frac{2}{3}g(x, Q^2) \otimes C_g(x, Q^2) + F_{2c}^{\mu N}(x, Q^2), \end{aligned} \quad (4)$$

with

$$F_{2c}^{\mu N}(x, Q^2) = e_c^2 x g(x, Q^2) \otimes H_{2g}^\mu(x, Q^2). \quad (5)$$

The massless quark and gluon coefficient functions,  $C_q$  and  $C_g$ , were calculated in [25, 26] (in our notation,  $n_f = 1$  in Eq. (B.6) of [26]). The partonic cross section for the production of heavy quarks pairs,  $H_{2g}^\mu$ , was calculated in [27], and can also be found in [15].

Similarly, in the neutrino case we have:

$$\begin{aligned} F_2^{\nu N}(x, Q^2) &= x \left[ \frac{(1 + |V_{ud}|^2)}{2}(u + \bar{u} + d + \bar{d})(x, Q^2) + |V_{us}|^2(s + \bar{s})(x, Q^2) \right] \otimes C_q(x, Q^2) \\ &+ 2g(x, Q^2) \otimes C_g(x, Q^2) + F_{2c}^{\nu N}(x, Q^2), \end{aligned} \quad (6)$$

$$\begin{aligned} F_{2c}^{\nu N}(x, Q^2) &= \xi \left[ \frac{|V_{cd}|^2}{2}(u + \bar{u} + d + \bar{d})(\xi, \mu^2) + |V_{cs}|^2(s + \bar{s})(\xi, \mu^2) \right] \otimes \\ &(\delta(\xi - 1) + H_{2q}^\nu(\xi, \mu^2, \lambda)) + 2\xi g(\xi, \mu^2) \otimes H_{2g}^\nu(\xi, \mu^2, \lambda), \end{aligned} \quad (7)$$

with  $|V_{ud}| = |V_{cs}| = 0.974$ ,  $|V_{us}| = |V_{cd}| = 0.220$  and  $\lambda = Q^2/(Q^2 + m_c^2)$ . The scaling variable for massive particles, in the case that the strange quark is treated as massless but the charm quark as massive, is given by:

$$\xi = x \left( 1 + \frac{m_c^2}{Q^2} \right). \quad (8)$$

The massive coefficient functions in Eq. (7),  $H_{2q}^\nu$  and  $H_{2g}^\nu$ , are the  $\mathcal{O}(\alpha_s)$  corrections to the  $W^+s \rightarrow c$  process:  $H_{2q}^\nu$  corresponds to the  $W^+s \rightarrow cg$  correction, while  $H_{2g}^\nu$  corresponds to the  $W^+g \rightarrow c\bar{s}$  fusion term. They were calculated in [28], and a factor of  $\alpha_s(\mu^2)/2\pi$  was buried in them. Eq. (7) agrees with the corresponding expression in Ref.[11].

For the calculations, we initially used the GRV98 [18] parameterization for the 3 light quarks and for the gluons, defined in the  $\overline{MS}$  scheme. If the NMC and the CCFR data are to be compatible, they should be described by the same parton distributions through Eqs. (4)-(7). Fig. 2 shows the CCFR data points as a function of  $Q^2$  for fixed  $x$ , against the LO (squares) and the NLO (solid triangles) theoretical calculations, with  $\mu^2 = Q^2 + m_c^2$  for the factorization scale in Eq. (7) and  $m_c = 1.4$  GeV. Since NLO calculations consistently incorporate all necessary charm mass effects, the slow rescaling corrections have to be removed from the data. This is done by using the correction factors supplied by the CCFR Collaboration [16]. The data shown in Fig. 2 have been corrected for nuclear effects by calculating the heavy target corrections specifically for neutrinos. The CCFR data is generally well described by both the LO and the NLO approaches, although the NLO calculation is superior for several data points. The points at  $x = 0.05$  and at  $x = 0.07$ , however, appear to be systematically below the experimental error bars.

The NMC data, shown in Fig. 3, is also well described by Eqs. (4) and (5), although the theory at the LO and at the NLO level has a slight tendency to be above the experimental data in the region where  $x$  is small. This is an important point in comparing the muon and neutrino  $F_2$  structure functions, because of the factor of 3 which multiplies  $F_2^{\mu N}$  in the difference  $(5/6)F_2^{\nu N} - 3F_2^{\mu N}$ , which is plotted in Fig. 1.

As we mentioned previously, the results are dependent on the parameterization used. To illustrate this point, we also calculated the structure functions  $F_2^{\nu N}$  and  $F_2^{\mu N}$  using the CTEQ [20] (CTEQ5) parton distributions. These are shown in Figs. 2 and 3, where the LO results are stars and the NLO results are open triangles. The CTEQ parton distributions give comparable fits to the neutrino and muon structure functions as was obtained with the GRV98 parton distributions. However, for the difference between the



neutrino and muon structure functions given by Eq. 1, which is plotted in Fig. 1, the CTEQ model gives better agreement with the data, as can be seen by comparing the solid circles with the open triangles. The NLO calculations with CTEQ parton distributions are essentially always within one standard deviation of the data in Fig. 1. We also carried out calculations using the MRST [19] (MRST99) parton distributions <sup>||</sup>. The MRST fits to the neutrino and muon structure functions are not shown, but the agreement with data is comparable to that for the GRV98 and CTEQ models. In Fig. 1 the NLO fits using MRST are plotted as the inverted solid triangles. The fit to experiment is very similar to that obtained with the CTEQ distributions.

Our approach allows a fully consistent comparison between theory and experiment. The slow rescaling corrections used by the CCFR Collaboration are quite large, as can be seen in Fig.1 (the difference between the solid circles and solid squares), and slow rescaling corrections play a major role in the disagreement between the CCFR and NMC data. Note that after applying the slow rescaling corrections (solid squares), the results should be compared to the massless LO calculations (open squares and stars), or to a massless NLO calculation. Thus the slow rescaling corrections suggest very large CSV contributions. This is a completely different conclusion from that based on our NLO calculations, where the solid circles should be compared with the triangles in Fig. 1.

We stress the importance of a correct treatment of the charm mass, along with shadowing corrections calculated specifically for neutrinos and not taken from muon data. These two effects allow the experimental data to come within the range of perturbative QCD. In the particular case of charm threshold effects, instead of trying to correct the experimental data by the use of the slow rescaling variable, we keep the data with no quark mass corrections, and perform a QCD calculation which incorporates the effects of a massive quark. We also calculated the ratio of longitudinal and transverse structure

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<sup>||</sup>Since a LO MRST gluon distribution is not available,  $F_{2c}^{\mu N}$  in Eq. (5) has to be calculated with the NLO gluon distribution. However, since the difference between  $F_{2c}^{\mu N}$  calculated with the NLO MRST gluon and with the LO GRV98 gluon distribution is small, this approximation has no sizable effect on our final result.

functions both for muon ( $R^\mu$ ) and neutrino DIS ( $R^\nu$ ), using the full NLO formalism with all massive quark effects. The results for  $R^\nu$  and  $R^\mu$  are shown as solid and dashed lines, respectively, in Fig. 4. The dash-dotted line is the Whitlow parameterization [29] of the world data on  $R^\mu$ . Both  $R^\mu$  and  $R^\nu$  are within the error bars of the available data in the kinematical region of our analysis ( $x < 0.1$  and  $Q^2 > 3.0 \text{ GeV}^2$ ) and are very close to the Whitlow parameterization of  $R^\mu$ , which was used by the CCFR Collaboration in the extraction of the structure functions. We also calculated  $R^\nu$  by assuming that  $R^\nu = R^\mu$  when  $m_c = 0$ , and using the Whitlow parameterization for  $R^\mu$ . The slow rescaling variable (implemented in LO) then accounts for the charm mass effects, as shown in dotted line. We see that the differences between  $R^\nu$  and  $R^\mu$  are similar in the full NLO calculation and the slow rescaling formalism. The slow rescaling correction used by the CCFR Collaboration effectively corrects for the difference between  $R^\nu$  and  $R^\mu$  in LO. Removing these corrections corresponds to the structure functions extracted under the assumption that  $R^\nu$  and  $R^\mu$  are the same. Then, the difference between the experimental structure functions,  $(5/6)F_2^\nu - 3F_2^\mu$ , will only involve a contribution from the difference between  $R^\nu$  and  $R^\mu$ . Since the full NLO calculation correctly accounts for this difference, the calculated quantity,  $(5/6)F_2^\nu - 3F_2^\mu$ , should be compared with the *uncorrected* data.

In summary, we see that a direct comparison of the CCFR  $\nu$  data and the NMC  $\mu$  data with a NLO QCD calculation leads to a much more consistent picture, if the nuclear corrections on Fe are made specifically for neutrinos. In order to make the comparison directly between the NLO calculation and the data, the “slow rescaling” correction had to be removed from the data. As this new analysis leads to a much less dramatic discrepancy than earlier work, it is consistent with the conclusion of the recent analysis of  $p\bar{p}$  data on  $W$ -asymmetry [33]. We observe that the data is still systematically above the NLO calculation based on the GRV98 distributions, while it is in quite good agreement with calculations based on either the MRST or CTEQ distributions. For the present, the possibility of detecting any residual charge symmetry violation depends on resolving this uncertainty in our knowledge of the strange quark distribution.

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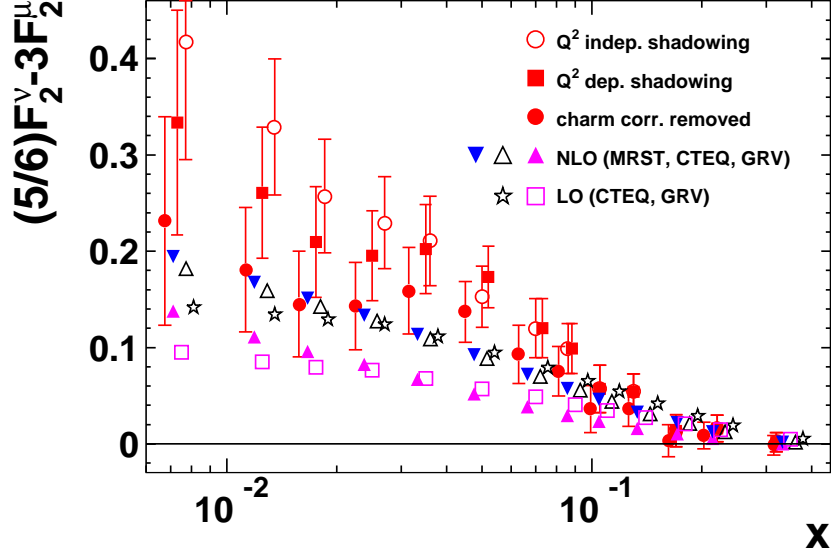


Figure 1: Comparison between theory and experiment for the difference  $\frac{5}{6}F_2^\nu - 3F_2^\mu$ , which is sensitive to deviations from charge symmetry in the parton distributions. The open circles use the original CCFR data, where the nuclear corrections to the  $\nu$  data are taken from muon measurements [4]. The solid squares involve the same data, but the shadowing corrections have been made explicitly for neutrinos [6, 17]. The solid circles are the same as the solid squares except that the “slow rescaling” correction has been removed. The open squares, stars and the triangles are respectively LO (massless) and NLO calculations, including charm mass effects [15] and using different parametrizations for the parton distributions. (Note that the theoretical calculations are all made at the *same*  $x$  and  $Q^2$  as the data, but displaced slightly for clarity.)

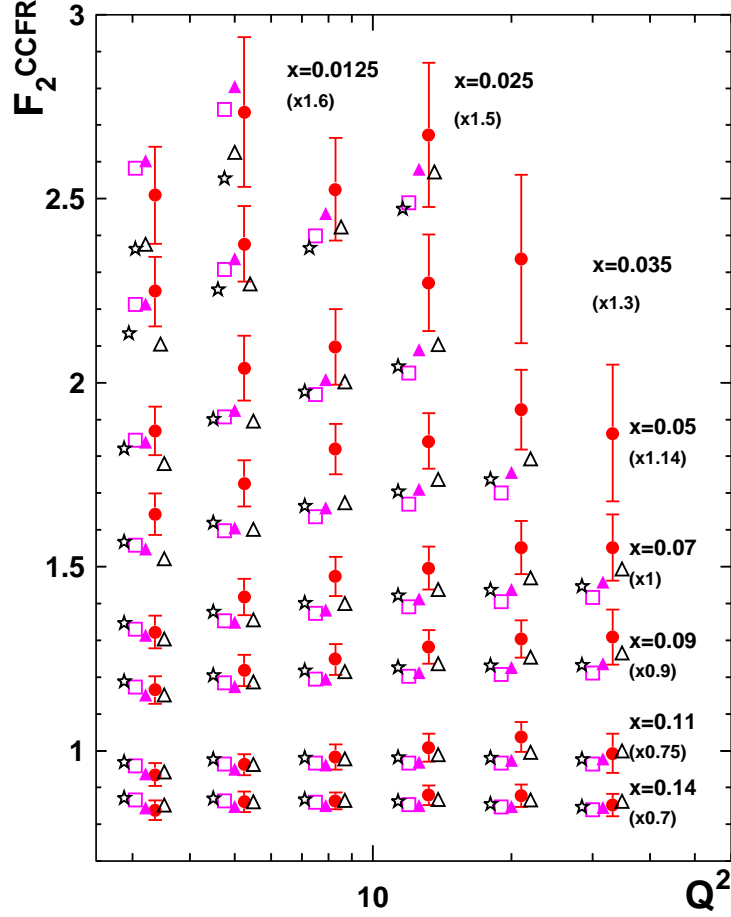


Figure 2: The  $F_2^{\nu}$  structure function as measured for neutrino charged-current DIS by the CCFR collaboration (solid circles), compared to LO and NLO QCD calculations. GRV98 parton distributions [18]: LO = open squares; NLO = solid triangles. CTEQ parton distributions [20]: LO = stars; NLO = open triangles. (Note that the theoretical calculations are all made at the *same*  $x$  and  $Q^2$  as the data, but displaced slightly for clarity.) The data have been corrected for shadowing, but the “slow rescaling” correction, present in the original CCFR data, has been removed.

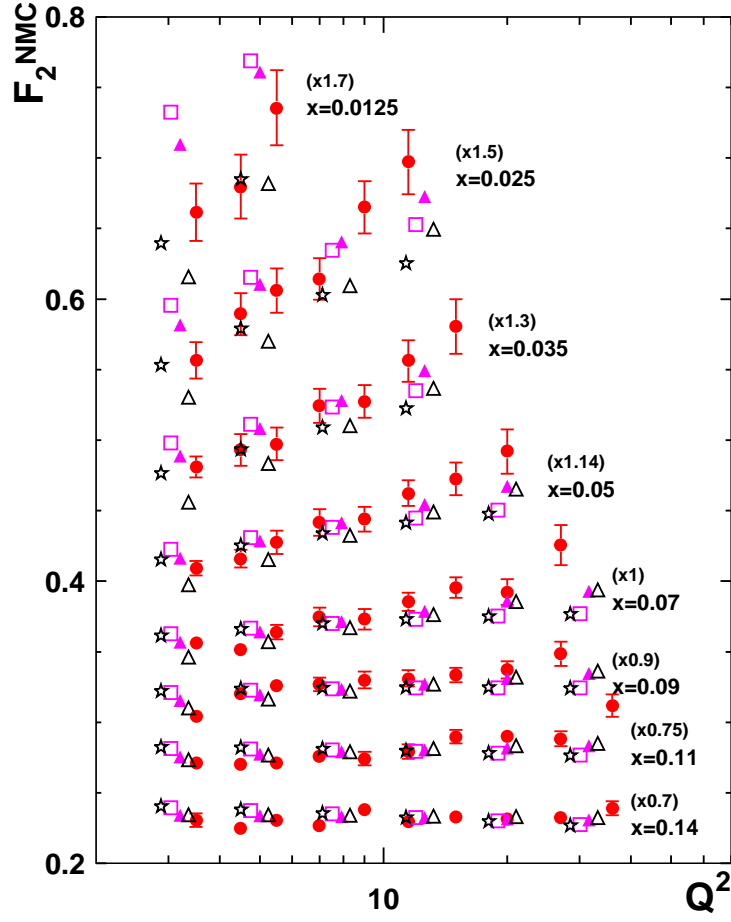


Figure 3: The  $F_2^\mu$  structure function as measured in muon DIS on deuterium by the NMC collaboration (solid circles), compared to LO and NLO QCD calculations using the GRV98 and CTEQ parton distributions [20, 18]. The notation is that of Fig. 2.

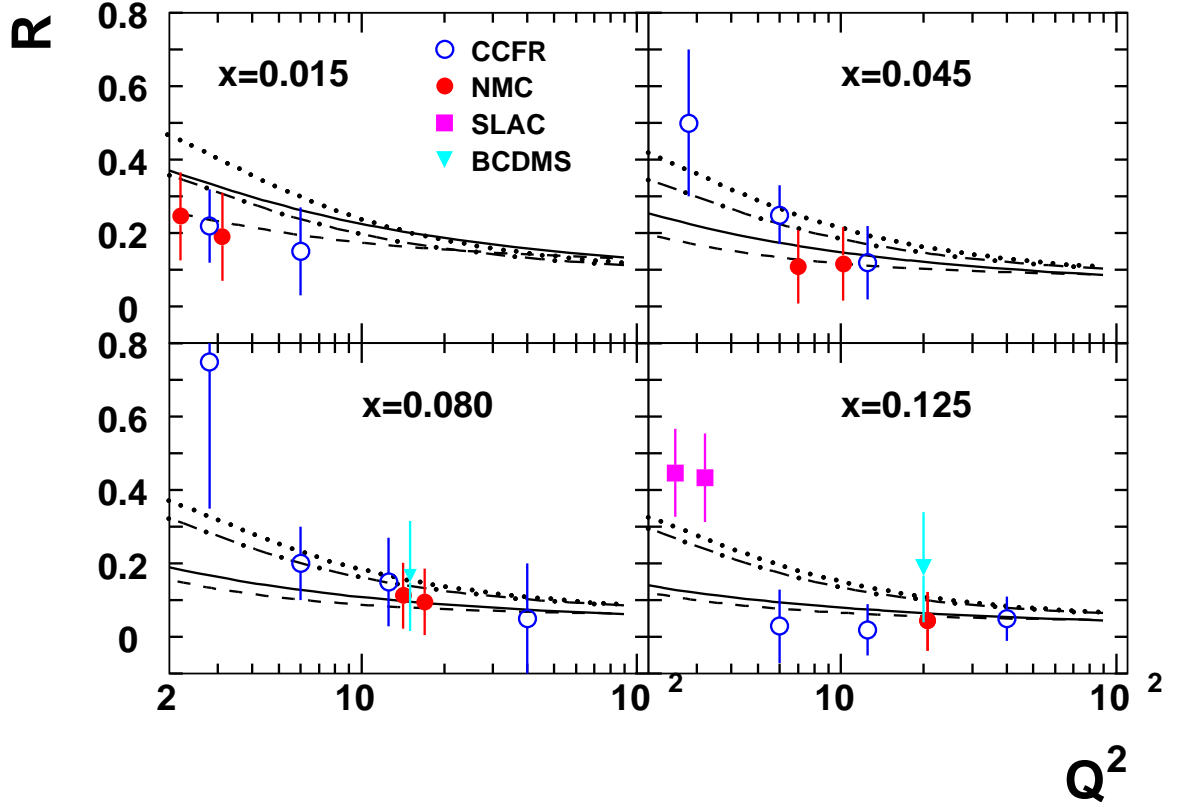


Figure 4: The ratio of the longitudinal and transverse structure functions calculated in NLO for neutrino (solid line) and for muon (dashed line) DIS. The dash-dotted line stands for the parameterization of the world data on  $R$  [29]. The dotted line is the result for  $R'$  using the Whitlow parameterization and the slow rescaling formalism. The data are from Refs. [29, 30, 31, 32].

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